Overview of Acceleration for a Neutrino Factory

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This paper is an overview of the acceleration issues for a Neutrino Factory. It will discuss the types of acceleration used for muons in different energy regimes, the choices of RF frequency, the injection and extraction for accelerator rings, and the cost considerations.

1. INTRODUCTION

This paper provides an introduction to acceleration for a neutrino factory. We will discuss the RF frequency choice and the types of acceleration used for muons in different energy regions. At lower energies linacs are the most effective choice. At higher energies recirculating linear accelerators (RLA) and fixed field alternating gradient (FFAG) rings are favored. The accelerating rings are not as effective as the linac for acceleration per unit length, however they are more cost effective in the high energy regime. An important issue for the accelerating rings is how to inject and extract the beam. For the high energy FFAG ring, the injection/extraction system is expected to be technically beyond that which has been used so far for high energy accelerators, however it is not believed to be technically impossible. The accelerator system is a significant fraction of the cost of a neutrino factory. The choice of which type of accelerator system to use at each energy regime is made by optimizing the relative costs for each system and selecting the lowest cost. The cost for the accelerator system of study 2-A[1] is 2/3 of the cost of the previous study 2 [2].

2. PARAMETERS

One must first choose one or more RF frequencies for the acceleration systems. The part of the neutrino factory preceding the acceleration, the so-called "front end," is one of the main factors in determining this. The US neutrino factory design breaks the large bunch coming off the target into many smaller bunches at 200 MHz. A higher frequency would have a smaller energy acceptance, and thus would capture less efficiently. A lower frequency would require impractically large cavities to achieve sufficient gradients to have a larger energy acceptance than the 200 MHz system. Furthermore, the lower frequency would require a significantly longer bunching section. Thus, the acceleration frequency will be forced to be a multiple of 200 MHz.

The NuFACTJ study [3] instead captured the entire beam off of the target in a single RF bucket. In this case, the longitudinal size of the beam requires very low frequency RF to be used. We find this scenario undesirable due to the significantly lower accelerating gradient available at these low frequencies.

The remaining question for the acceleration RF frequency is whether to use 200 MHz or a multiple thereof. The longitudinal acceptance is significantly reduced if one uses higher-frequency RF, which leads one to choose 200 MHz RF. In principle transverse acceptance will be independent of the RF frequency, as long as the lattice cells are shortened inversely with the RF frequency. Unfortunately, this would require magnetic fields which are proportional to the RF frequency. Thus, it is often easier to achieve large transverse acceptance with lower RF frequency. Finally, the circulation time in the RLAs and FFAGs is significantly smaller than the cavity fill time and any usable RF frequency; thus, the stored energy in the cavities will be used for acceleration. Higher frequency RF has a lower stored energy, and thus fewer turns would be possible

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in these multiple-pass systems with higher frequency RF than with lower frequency.

We are proposing different kinds of acceleration for the different energy regions during the acceleration. For muon energies under 1.5 GeV, a linac is used. A linac accelerates the fastest, but is the most expensive per GeV. For energies between 1.5 and 5 GeV, an RLA is used. It accelerates at about half the rate of a linac, but since the beam passes through the same linac 3.5 times it has 1/3.5 the RF cost. The minimum energy to inject into the RLA is $\sim$1.5 GeV because of phase slip in the RLA linac due to velocity variation with energy. For energies above 5 GeV a FFAG accelerator is used. This accelerates at a quarter of the rate of the linac because a larger fraction of the ring is taken up by magnets, but since an FFAG doesn't require the complex switchyard of an RLA, one can have more turns ($\sim$15 in our application) than the RLA, reducing significantly the RF cost. The minimum useful energy for an FFAG accelerator is about 5 GeV, which comes from a cost comparison with the RLA.

2.1. Linac Design

The linac is designed with a normalized transverse acceptance of 30 π mm-rad. Since the cavities will operate at 200 MHz, the maximum radius of the cavity iris is 23 cm and the length of a cavity is 75 cm (additional space is needed for input couplers, etc.). The linac is divided into three regions, each optimized for its energy band and each with its own cryomodule design. The first part has only one single-cell cavity per period and handles the momentum range from 0.27 to 0.38 GeV/c. The second part has one 2-cell cavity per period and handles the momentum from 0.38 to 0.57 GeV/c. The final part has two 2-cell cavities per period and handles the momentum up to 1.5 GeV/c.

2.2. Recirculating Linac Accelerator

The linac is followed by a 3.5 pass RLA which raises the energy from 1.5 to 5 GeV. Both a dogbone and a racetrack RLA geometry have been considered. The accelerating portion of the RLA uses four 2-cell superconducting RF cavities per cell with a quadrupole triplet to provide the focusing. The dogbone RLA is favored for the Study 2-A design since for a given number of linac passes, it has a larger energy separation at the switchyard than a racetrack geometry, simplifying the switchyard design. To keep the phase variation (due to time-of-flight variation with energy) along the linac reasonable, the beam is injected into the RLA at the center of the linac.

2.3. FFAG Accelerating Rings

The RLA is followed by two successive FFAG rings that increase the muon energy from 5 to 10 GeV and 10 to 20 GeV, respectively. The FFAG rings use combined function magnets arranged in a FDF triplet configuration. Typically two types of the FFAGs have been used for muon acceleration: scaling and non-scaling varieties.

Scaling FFAGs are the traditional type of FFAG. The fact that they are non-isochronous makes them less cost-effective for a 200 MHz RF system than the non-scaling FFAGs which we use, since the non-scaling FFAGs can be made isochronous within the energy range of the accelerator. These non-scaling FFAGs seem to work best with an energy range of around a factor of 2, which leads to the two stages of FFAGs for the neutrino factory.

2.3.1. Non-Scaling Lattice Choice

Triplet, FODO and doublet lattices for a non-scaling FFAG can be designed to the same requirements. J.S. Berg [4] has optimized each of these styles of lattice using a costing algorithm. The optimization varied parameters while keeping the same requirements on energy swing, minimum magnet spacing, length for RF, isochronicity, and acceptance. Table 1 compares parameters and costs of the optimized lattices of each style for the 10–20 GeV FFAG ring. The differences between the lattice styles are not large, but the doublet lattice is the smallest, cheapest and has the lowest decay losses of the different styles. It should be noted that for the 10–20 GeV FFAG, that the cost per GeV is less than half that of the RLA.

Table 1
Comparison of the FODO, Triplet (FDF) and Double (FD) non-scaling lattices for the 10–20 GeV FFAG rings.

	FODO	FDF	FD	RLA
Magnets	210	255	186	
Circumference	681	521	481	1300
Decay, %	10.4	10.1	8.5	5.0
Cost/GeV $M	10.2	9.0	8.7	20.5

3. INJECTION AND EJECTION

The requirements for a kicker magnet to inject (extract) a beam into (out of) an FFAG ring are expected to be significant. The minimum required kicker stored energy and voltage for a beam with normalized acceptance $A_n = 0.03$ m, kicker length $L = 1$ m, and rise time $\tau = 1$ μs is

$$U = \left(\frac{m_\mu^2 8}{\mu_o c^2}\right) \frac{A_n^2}{L} = 710 \text{ J}$$

$$V = \left(\frac{4 m_\mu}{c}\right) \frac{A_n}{\tau} = 42 \text{ kV}$$

The voltage required is large, but not unreasonable, however the kicker stored energy is quite large. The largest kickers used for high energy physics accelerators store 10–20 J. The above numbers are actually an underestimate due to the horizontal aperture being larger than the final beam size because of the dispersion in the beam, the finite septum thickness, the finite permeability of the kicker flux return, etc. An example of an extraction lattice has been worked out for the 10–20 GeV FFAG ring which requires a stored energy $U = 3400$ J and voltage $V = 200$ kV. This kicker uses significantly more stored energy than any kicker previously built, however it uses power comparable to that needed for induction linacs. Magnetic amplifier power supplies (as used for DARHT) can supply the required stored energy with the required rise time.

4. COSTS

The design choices of the linac, RLA, and FFAGs were driven by cost. It appears that the acceleration costs of Study 2-A are about 67% of that found for Study 2. In addition the acceptance of the full system was increased from 15 to 30 π mm-rad. Table 2 shows the costs for the different acceleration components for Study 2 and Study 2-A. The primary cost savings comes from the falling acceleration costs per GeV for FFAGs at higher energies. The costs listed in the table are not normalized. They do not include management overheads, and ignore inflation corrections. These numbers can be used for comparisons between the studies.

Table 2
Costs for the accelerator components used in Study 2 and Study 2-A. The costs are not corrected for management costs and escalations.

	Study 2		
	GeV	$M	$M/GeV
Linac	0.3–2.5	132	60
RLA	2.5–20	355	20.3
Total		487	

	Study 2-A		
	GeV	$M	$M/GeV
Linac	0.3–1.5	70	100
RLA	1.5–5	82	20.5
FFAG1	5–10	80	16
FFAG2	10–20	98.3	9.8
Total		330	

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